

FABRICATION OF GRANULATED FOAM GLASSES FOR LIGHTWEIGHT CONCRETE APPLIED FOR THERMAL AND SOUND INSULATION

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Abstract

Granulated foam glass aggregates were fabricated and applied as fillers in lightweight concrete. Soda lime silicate based glass was used as the main raw material in the foam glass process. Firing temperatures in the range of 820-850°C were suitable for the foaming process. Granulation was processed using a rotary granulator and heated to expand in an electric rotary furnace. Foaming at 840°C showed overall properties suitable for applying as a filler in lightweight concrete fabrication e.g. low density, high porosity, uniform of pore size. Foam glass granules processed at 840°C were mixed with cement paste in the ratios of 5, 10, 15, and 20 vol% to study for bulk density, compressive strength, thermal conductivity, thermal resistivity and sound absorption. Overall, increasing foam glass content in concrete caused a decrease in bulk density, compressive strength and thermal conductivity coefficient. In contrast, thermal resistance and sound absorption coefficient of the foam glass filled lightweight concretes improved significantly.

Keywords: Concrete; foam glass; lightweight; sound absorption; thermal conductivity

Introduction

Expanded foam glass or cellular glass is a porous material made from glass powder mixed with a foaming agent or a combination of foaming agents to generate bubbles, mostly compounds of carbon at high temperature (Fernandes *et al.*, 2009, König *et al.*, 2016, Qu *et al.*, 2016). Soda lime silicate glasses have softening temperatures around 600-700°C (Petersen *et al.*, 2017) in which glasses can be expanded just above this temperature range with

suitable foaming agents. The basic principle of foaming process is to generate a gas bubbles within a compacted glass powder that is being heated at high temperature above softening point of the glass. The gases generated expand as bubbles and produce a structure of cells to form a porous solid glass mainly closed-cell structure (Souza *et al.*, 2017, Wei *et al.*, 2017).

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Foam glass have excellent properties such as low density, low thermal conductivity, sound insulation, corrosion resistance, fire resistance, long life, low cost and environmentally friendly. It can in some cases withstand high compressive forces and is non-flammable and non-toxic (Zhang *et al.*, 2016; Souza *et al.*, 2017; Wei *et al.*, 2017). Foam glass filled concrete can be advantageous in terms of lightweight, heat insulation, sound insulation and low water penetration (Bumanis *et al.*, 2013; Šeputytė-Jucikė *et al.*, 2016; Zhu *et al.*, 2016; Adhikary *et al.*, 2021).

König *et al.* (2016) investigated the influence of glass particle size on the foaming process of foam glass by preparing low density foam glasses from cathode-ray-tube panel glass using carbon and MnO_2 as the foaming agents. They found that as the particle size (D50) increased from 100 to 200 μm , the apparent density of foam glasses increased from 0.2 to 0.3 g/cm^3 when fired at 835°C. Closed porosity (CP) in relation to the particle size (D50) and density of the foam glasses prepared at 835°C remained almost constant at 98-100%. Thermal conductivity (λ) of the foam glasses prepared with 0.93 wt.% carbon and 6.76 wt.% MnO_2 , heated at 5°C/min to 835°C and held for 30 min gave the values of 0.115-0.160 W/(m.K).

Bumanis *et al.* (2013) studied the relation between mechanical and thermal properties of lightweight concrete made from expanded glass aggregates. The mixture proportions contained Cement Cemex, limestone, sand, expanded glass and chemical admixtures. They found that the addition of expanded glass from 33% to 45% decreased flowability and cone slump and density of fresh concrete. Mechanical properties of hardened concretes after 28 days showed a slight decrease of compressive strength from 5.8-4.0 MPa but no significant change in flexural strength. Concretes containing expanded glass gave low thermal conductivity values between 0.140-0.163 W/(m.K).

The objectives of this study were to understand the effect of firing temperature on the structure of foam glass granules fabricated in an in-house design electric rotary furnace. Crude glycerol from biodiesel refinery plant was utilized as an effective foaming agent which has not been investigated in other related literatures. Sodium silicate were used as a binder and a fluxing agent. The suitable granulated foam glass, selected based on uniform pore size and low bulk density, was added to cement paste, without the addition of sand or any other cement admixture, to fabricate lightweight concretes. The investigated properties included foaming behavior of foam glass, structure of foam glass, bulk density, compressive strength, thermal insulation and sound insulation of concretes.

Materials and Methods

The soda-lime silicate glass utilized in this study was obtained from consumable drink bottles. The glass composition was analyzed by X-ray Fluorescence Spectrometer WDXRF ZXS Primus, Rigaku, Japan) and gave a following composition in (wt%): 69.24 SiO_2 -12.43 Na_2O -13.80 CaO -2.39 MgO -1.50 Al_2O_3 -0.19 K_2O -0.15 Fe_2O_3 -0.02 P_2O_5 -0.07 TiO_2 . The glass was crushed into small fragments before transferring it into a 5 kg pot mill. Ball milling using alumina milling media was carried out for 4 h at 50 rpm to give fine glass powder. The glass powder was then sieved through 180 μm using Retsch AS 200 sieve shaker.

The composition for fabricating expanded foam glass contained 92 wt% soda-lime silicate glass - 2 wt% crude glycerol - 6 wt% sodium silicate. This composition was optimized by the authors (unpublished data) for best preparation into small granular shape compact as well as good foaming behavior at 800-900°C. Sodium silicate (Amarin Ceramics) was used as a fluxing agent and a binder. Fluxing effect occurred when sodium was incorporated in the soda-lime silicate glass structure and formed non-bridging oxygens in $[\text{SiO}_4]$ corner-sharing tetrahedra (Hesky *et al.*, 2015). The binding effect helped holding the compacted samples during heating process and prevented sample for collapsing. Crude glycerol was used as a foaming agent. The crude glycerol from Siam Absolute Chemical Co. Ltd. (Thailand) had been obtained from biodiesel refinery plant and consisted of 75-78 wt% glycerol compound based on the data sheet provided by the manufacturer. Other compounds listed by the manufacturer were methanol (<10%), water (10%) and polyglycerol esters (<5%).

Dilatometric analysis was tested on the soda-lime silicate glass sample (5 mm $\times$ 5mm $\times$ 3 mm) using Netzsch DIL 402 dilatometer operated at the heating rate of 10°C/min. This technique was utilized to investigate for the glass transition temperature and the dilatometric softening point. Granulation process was prepared by an in-house design granulator operated at 60 rpm with incline angle of 20° to give tiny granules (1-3 mm) then air dried at room temperature at least 2 days before transferring into an electric rotary furnace for the foaming process. Photomicrographs of dynamic characteristics of sintering was carried out on the compacted granules using an electric tube furnace (Carbolite, STF 16/180 UK) at a heating rate of 5°C/min. A digital camera (Nikon D90) was used to determine the foaming behavior of the compact granules obtained from the granulation process. This method was carried out to select for the best

processing temperature which resulted in foam glass with uniform pore size distribution in the bulk structure.

In the rotary foaming process, a heating rate of 5°/min was utilized from room temperature to the set maximum foaming temperature. The foaming time was 10 min at maximum set temperature after that the heating was switched off and rotary process continued during furnace cooling to room temperature to obtain foam glass granules. Foam glass granules were then sieved into granular size of 3-5 mm for lightweight concrete fabrication.

Ordinary Portland Cement SCG Type I was mixed with fresh water in the ratio of 1:0.5. Granular foam glass was then added at different ratios of 5, 10, 15, and 20 vol% and then cast on steel molds with dimensions of 50 mm × 50 mm × 50 mm and 8 specimens were prepared for each mixed concrete composition. These specimens were used for density measurement and compressive strength test. Cylindrical specimens were prepared with a diameter of 100 mm and a thickness of 30 mm for thermal and sound insulation test.

Bulk densities were measured with a 4-digit balance Sartorius BSA224S-CW for foam glass granules fabricated at different heating temperatures and also on the concretes after casting every 4 days until 28 days which assumed full hydration of the cement (de Castro and de Brito, 2013). Hydraulic press machine for concrete model TMC-12T was used to measure for compressive strength. Micrographs at high magnification were obtained by a scanning electron microscope (Hitachi Tabletop Microscope TM3030) under back scattered electron mode. For sample preparation, the samples were etched in 5%HF then ultrasonically cleaned and dried. Platinum coating by sputtering was carried out to reduce charging effect caused by high porosity of foam glass samples. Thermal Conductivity (K) and R-value were tested following ASTM C518 using EKO Instruments HC074-200. The uncertainty of test is ± 0.0003 W/m·K. Sound absorption coefficient were tested following ISO 10534-2:1998 ASTM E1050 with operating temperature at $23 \pm 2^\circ\text{C}$ and relative humidity at 50 ± 5 %RH.

Results and Discussion

Figure 1 shows the dilatometric analysis of the soda lime silicate glass. Heating from room temperature to about 540°C gave a linear relationship indicating a characteristic of a solid glass where it had a constant thermal expansion coefficient. Above this temperature, the glass transition, T_g was detected at

the first slope change at 543.0°C and the dilatometric softening point was observed at 597.4°C where the slope and microstrain became negative which indicated that sample was softened by the applied force of the pushrod in the dilatometer. To successfully prepare foam glass, the glass powder must have been softened far above the dilatometric softening point, usually 150°C above it so the glass powder partially melted on the particle surface and connected together during sintering that gases can be trapped inside and expand into larger bubbles by increasing gas pressure.

Figure 2 shows overall process for fabricating foam glass granulate. Figure 2(a) shows glass powder ($<180\mu\text{m}$) mixed with sodium silicate and crude glycerol. Figure 2(b) shows granular compacts (1-3 mm diameter) and Figure 2(c) shows an example of foam glass granules after heating in a rotary furnace at 850°C for 10 min. The granular compaction expanded greatly to form foam glass

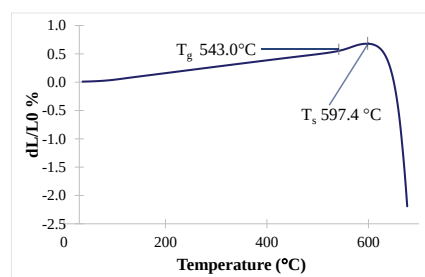


Figure 1. Dilatometric analysis of soda lime silicate glass

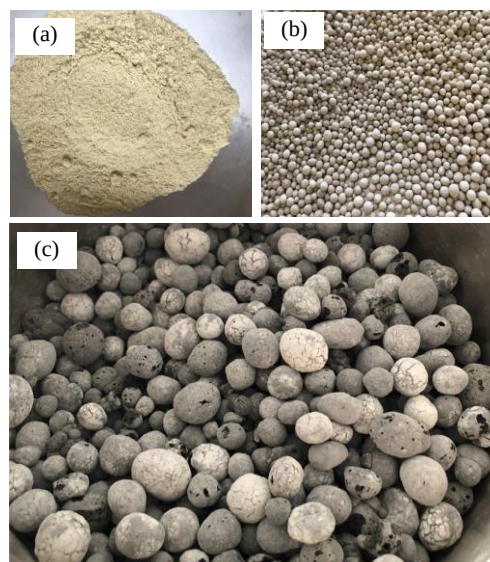


Figure 2. (a) Glass powder ($<180\mu\text{m}$) (b) Granular glass powder compacts (c) Foam glass granules after heating in a rotary furnace

granules. The surfaces were smooth and showed little porosity. Sodium silicate provided a binding effect to help the granulation process and also gave fluxing effect to the soda-lime silicate glass during heating in a rotary furnace which reduced glass softening point and this in turn, resulted in an easier foaming to expand the granules into rounded foam glass. Crude glycerol in general exhibits a much wider temperature range of thermal decomposition, giving relatively stable residues above 227°C. The residues of the main decomposition are much harder to eliminate via thermal which means that crude glycerol pyrolysis starting above 487°C, and leaving about 5% mass residue above 820°C. At high temperatures, thermal cracking reactions were predominant giving CO_2 , CO , H_2 . The decomposition phases were attributed to cracking of fatty acid methyl esters and pyrolysis residues (Hemings *et al.*, 2012).

Figure 3 shows Photomicrographs of dynamic characteristics at the heating rate of 10°C/min. Horizontal tube furnace and a digital camera were used for dynamic heating and image capturing as shown in Figure 3(a). The volume started to expand slightly at about 780°C and it was evident at 820°C (Figure 3(b)). Therefore this temperature was chosen as the first point for the foaming process in the rotary furnace. Figure 3(c) shows the expansion at 850°C and the volume expansion increased slightly under visual observation. In this investigation, obvious melting started at around 980°C. Figure 3(d) showed the heating at 1,100°C in which the glass melted under its own weight. Pores generated in the bulk structure collapsed at high temperature and the bulk sample became denser. At 1,150°C, the sample melted completely and after cooling to room temperature, it can be seen in Figure 3(e) that denser glass sample without porosity was obtained.

Figures 4(a-d) show internal cross sectional structures of foam glass granules fired in an electric rotary furnace at different temperatures; 820, 830, 840, and 850°C, respectively. Pore size range appeared similar (0.2-0.4 mm) for the specimens fired at 820, 830, and 840°C. However, firing at 850°C resulted in larger pore size mostly in the range of 0.6-1.0 mm. At this temperature and above, high pressure exerted on the low viscosity glass walls and caused the formation of larger closed pore cells. There were also some interconnected pores that gave rise to non-uniform pore distribution within the bulk structure. The use of crude glycerol as foaming agent generally gave small closed pores that dispersed quite well uniform within foam glass samples. There was an evolution of low pressure gas bubbles in the glass which resulted in small pores.

Although a variation of pore sizes were observed, larger pores were mostly observed at temperature from 850°C and above. In this study, firing at 840°C was chosen for the best foam glass granule fabrication to be applied into cement for lightweight concretes. This processing temperature also resulted in less scattered density values when average for 20 granules of each firing temperature. In this study, the bulk density values were 0.71, 0.59, 0.56, and 0.42 g/cm³ for the firing at 820, 830, 840, and 850°C, respectively.

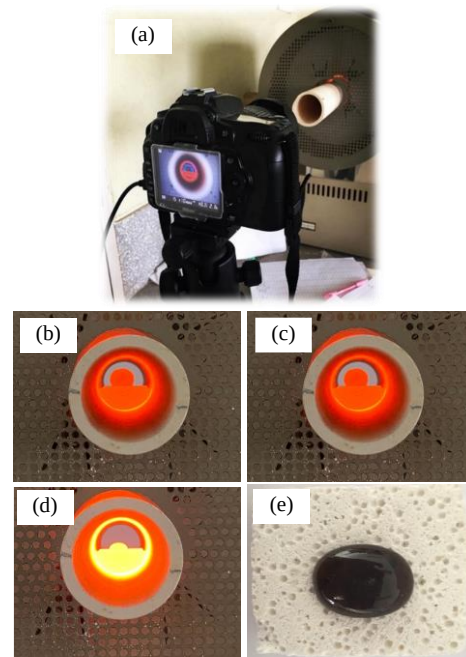


Figure 3. Photomicrographs of dynamic characteristics at the heating rate of 10°C/min (a) Equipment setup (b) 820°C (c) 850°C and (d) 1,100°C (e) After cooling from 1,150°C

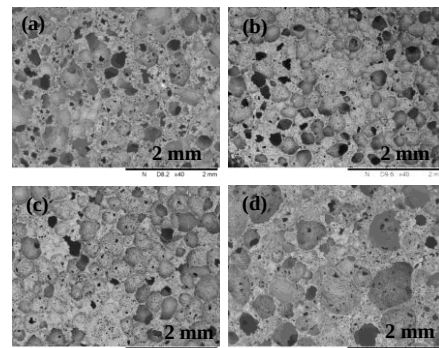


Figure 4. SEM micrographs of foam glass granules fabricated by rotary furnace (a) 820°C, (b) 830°C, (c) 840°C, and (d) 850°C. Scale bar 2 mm

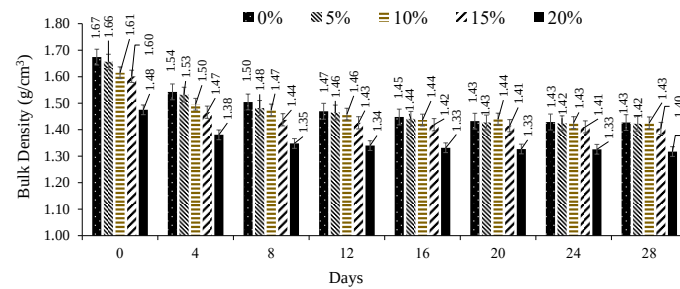


Figure 5. Bulk density of concretes measured for the periods of 0-28 days with 0%, 5%, 10%, 15%, and 20% foam glass granules

Figure 5 shows bulk density of concretes measured for the periods of 2-28 days with 0%, 5%, 10%, 15%, and 20% foam glass granule additions. General trends can be seen that the higher amount of foam glass addition, the lower the bulk density. After 2 days concrete samples can be demolded for the density measurement. The values of bulk density decreased slightly from day 4 to day 28 when the samples were left in room temperature for the hydration period.

Figure 6 shows compressive strength values of concrete samples after 28 days of hydration period.

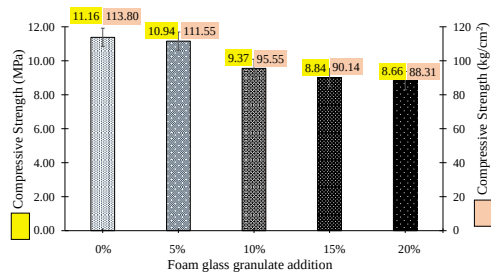


Figure 6. Compressive strength of concrete samples in MPa and kg/cm²

It was evident that the addition of foam glass granules reduced the strength. Without foam glass addition, the value was 11.16 MPa and the value decreased gradually to 8.66 MPa (25.34%) when 20 vol% of foam glass granules was added. The main component that gave dominant strength to concrete was the hydrated Portland cement. Foam glass which contained a lot of closed pores in the bulk structure weakened the structure in terms of mechanical strength (Yu *et al.*, 2016). Cracks under compressive load started to occur in the brittle foam glass first during the test. The cement system had the main role of binding the granules together. The higher the foam glass content in the concrete, the higher possibility of foam glass are in contact. Hence, cracks can propagate easily from one foam glass granule to another foam glass granule.

As far as the distribution of foam glass granules within concrete and the microstructures of fracture surfaces after compression test (Figure 7) were concerned, it can be seen in that the addition of 20% foam glass granules did not give uniform foam glass granule distribution within the concrete (Figure 7(a)). In some area, foam glass granule agglomeration can be clearly seen. During mixing

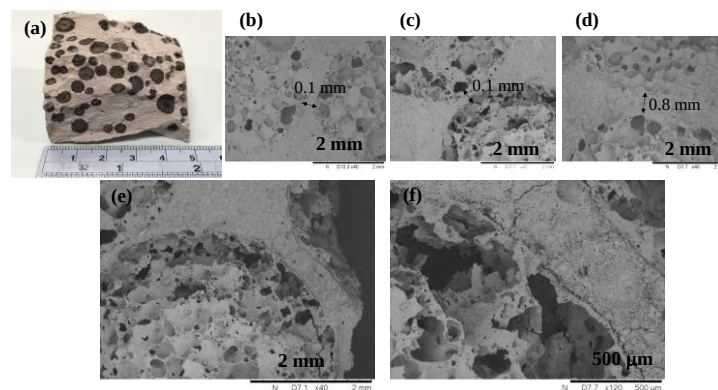


Figure 7. Concrete fracture surfaces after compression test (a) 20% foam glass granule addition (b)-(d) distances between foam glass granules (e)-(f) micro-cracks in foam glass and cement

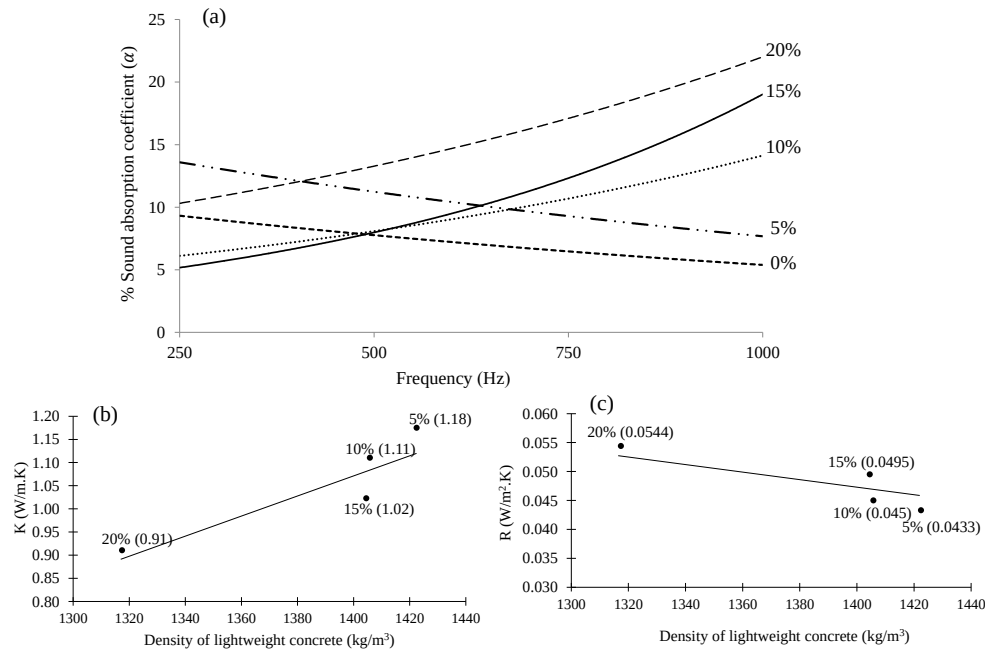


Figure 8. Sound and thermal insulation properties of concrete specimens with different foam glass content and tested after 28-day hydration (a) Sound absorption coefficient (b) Thermal conductivity (c) Thermal resistivity

of the portion with cement paste the granules may have been separated and floated in the paste due to different density. After the concrete had set in the mold, the distribution was then not so uniform. Figures 7(b-d) showed SEM micrographs that in some regions foam glass granules almost touched each other (0.1 mm and 0.8 mm) giving close distances between foam glass granules. This may have led to lower concrete strength. Most foam glass granules, however, had separation distances in the range of 2-4 mm. The scale bar in the SEM micrographs was 2 mm. In this study, in foam glass granules can be easily visually observed by eyes and also under SEM analysis. Example of internal crack is shown in Figure 7(e) in which the length is greater than 1 mm. Figure 7(f) showed a higher magnification SEM image where long crack path was observed between foam glass granule and cement paste and also crack path within cement paste itself. These can occur before compression test due to poor adhesion between foam glass granules and cement paste or it may have come from the grinding method for preparing sample for SEM.

Kidalova *et al.* (2012) and Alex *et al.* (2016) and mentioned about the distribution of lightweight matter in concrete had a significant effect on the compressive strength. The water molecule will accumulate at the interface between the lightweight aggregate and cement resulting in concrete weakness which is called “Interfacial Transition

Zone (ITZ)”. When the water evaporates it leads to small crack in micron size regime. This can cause crack propagation under compressive load. This behavior can also possible in our study which should not be ignored.

Figure 8 reports the data on sound and thermal insulation properties of the concrete specimens with different content of foam glass granules. In Figure 8(a), it was obvious that concrete containing high content of porosity, i.e. 20% foam glass addition, resulted in the highest sound absorption coefficient. The sound frequencies between 500-1,000 Hz was a normal range for music sound people talking. Therefore, if we consider at 750 and 1,000 Hz, a good trend of sound insulation was obtained for the addition from 10% to 20% foam glass in concrete. The 5% foam glass concrete composite did not follow the above mentioned samples. The causes of this adverse effect is not known but the value of sound absorption coefficient was calculated from the average of sum of all frequencies which in this sample was about 12%. This shows a decent sound insulating effect as compared with 0% foam glass sample which had an average sound absorption coefficient of 6%.

The results on thermal conductivity (K) and thermal resistivity (R) are shown in Figures 8(b) and 8(c). In Figure 8(b), lowest K value in this study was 0.91 W/m.K which was found in the concrete with 20% foam glass addition. Less amount of foam

glass addition led to higher K value such as 5% foam glass addition in concrete gave highest K value at 1.18 W/m.K. As far as thermal resistivity was concerned, the trend was opposite to that of thermal conductivity. It can be seen in Figure 8(c) that the highest R value was 0.0544 W/m².K with 20% foam glass. This R value decreased to 0.0433 W/m².K for 5% foam glass addition. For good thermal insulation, higher R and lower K values are required. The applications can be applied for walls in air-controlled buildings when electricity cost is a prime concern. Pores within foam glass granules contain air which is poor heat conductor and will obstruct the passing of heat therefore heat transfer was not efficient.

Conclusions

Granulated foam glasses were fabricated successfully in the temperature range 820-850°C using crude glycerol as a foaming agent and sodium silicate as a binder and fluxing agent. Heating at 840°C gave uniform pore size (0.2-0.4 mm), closed cells, as well as low bulk density of 0.56 g/cm³. The glass mixture showed high evident of melting behavior at 1,100°C. Foam glass granules mixed with cement paste from 5 to 20 vol% and hydrated in air for 28 days were prepared for lightweight concrete composites. Overall, increasing foam glass granule content caused a decrease in bulk density, compressive strength and thermal conductivity. The lowest K value obtained in this study was 0.91 W/m.K. On the other hand, thermal resistance and sound absorption coefficient increased when foam glass was added in the concrete system.

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